HOW MUCH HYDROGEN DO WE NEED AND WHERE? A SPATIALLY DETAILED ESTIMATION OF THE POTENTIAL HYDROGEN DEMAND IN THE FUTURE AVIATION AND INDUSTRY SECTOR FOR ITALY

Francesco Mezzera[1]*, Giuseppe Muliere[1], Fabrizio Fattori[2], Giulia Novati[1,3], Mario Motta[1]

[1]Politecnico di Milano, Department of Energy, Via Lambruschini, 4a, 20156 Milan, Italy

[2]University of Insubria, Department of Theoretical and Applied Sciences , Via J.H. Dunant, 3, 21100 Varese, Italy

[3] University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria, 27100, Pavia, PV, Italy[1]

*Corresponding Author: francesco.mezzera@polimi.it

ABSTRACT

The decarbonization of the energy system involves the need for several new technological solutions. Hydrogen emerges as a potential key player, particularly in sectors where electrification is impractical (due to economic reasons or plant design complexity), such as aviation and certain industries. However, a comprehensive understanding of where demand and supply for this energy carrier might intersect is lacking. This lack is determined by the early stage of development of the hydrogen market but it also contributes to shaping its evolution, in a reciprocal cause-and-effect manner.

This article introduces a methodology for estimating the potential hydrogen demand and its geographical distribution within specific classes of the transport and industrial sectors. Using the Italian case study, open-access data with varying spatial resolutions are collected: (i) electrical loads, (ii) the fossil fuel consumption and (iii) the estimated thermal and electrical annual energy needs for the industry; (iv) the number of flights departing from each airport for aviation throughout the year and lastly (v) the distribution of workers and active enterprises per category.

The developed tailored methodologies aim to estimate the energy needs of both sectors in a fully decarbonized scenario. Industrial demands are differentiated by class and temperature level, allocated across regions through the distribution of workers per census section (subareas of a municipality). A focus on refining subsector is provided, with a first-attempt estimation on green molecules needed to substitute fossil feedstocks. As regards the aviation sector instead, it is characterized by a dedicated regression model associating fuel consumption with the distance travelled by each flight departing from the observed airport. Subsequently, we define a plausible energy mix, estimating the energy vectors needs. Hydrogen and its derivatives demands (i.e., liquid kerosene) are assessed at the same spatial resolution as industry (census section). The main outcomes of the analysis allow to identify potential clusters of demand across the Italian energy system, guiding the selection of areas suitable for the development of hydrogen hubs or distributed local hydrogen grids (e.g., production, transport, storage close to the end-use). In a decarbonized scenario, the results show a potential annual hydrogen demand around 600 TWh within the two sectors (i.e., ~18 Mt_{H2}/y), of which almost 73% is destined for decarbonizing refining products (~433 TWh), while the remaining share destined for industrial thermal needs (154 TWh) and 9 TWh for aviation purposes in pure form. This first assessment might serve as a base for further studies, enabling policymakers to identify and tailor measures for specific subsectors and geographical areas and aiding hydrogen-related projects in identifying viable development locations, fostering synergies with local players, and capitalizing on economies of scale.

---

[1] Part of this paper and related research have been conducted during and with the support of the Italian national inter-university PhD course in Sustainable Development and Climate change

https://doi.org/10.52202/077185-0010

1 INTRODUCTION

In recent years, the imperative to accelerate the ecological transition has prompted a reevaluation of national and international energy strategies across European Union (EU) countries, notably influenced by the "Fit for 55" (European Council & Council of the European Union, 2021) and "REPowerEU" (European Council & Council of the European Union, 2022) packages. These initiatives aim to reduce greenhouse gas emissions by 55% from 1990 levels by 2030 and strengthen energy security. The decline in fossil fuel imports, especially natural gas, necessitates a rethinking of end-use sector consumption, advocating for a transition to new renewable technology options, including, but not limited to, electrification. Hydrogen, a key focus for decarbonizing hard-to-abate sectors like heavy transportation and industry, historically derives from fossil natural gas or coal, releasing CO_2 in atmosphere during the production process. To reduce its carbon footprint, alternative options are explored, as for example hydrogen produced via water electrolysis using electricity, with only oxygen as by-product of the chemical reaction. The carbon intensity in this case may vary depending the power generation technology used (e.g., dedicated renewable power plant v. electricity from the power grid).

Currently, hydrogen is used in some industrial applications, primarily for chemical production (e.g., fertilizers) and refining processes (e.g., Sulphur removal), often produced on-site via conventional methods. To drive renewable hydrogen deployment, European authorities have introduced mechanisms like the “Green Deal Industrial Plan” and the “Net-Zero Industry Act” (European Commission, 2023), with the goal to ramp up the manufacturing of renewable technology within EU borders. Similar efforts extend to the transport sector through packages like "FuelEU Maritime" (European Council & Council of the European Union, 2023a) and "ReFuel EU Aviation" (European Council & Council of the European Union, 2023b), setting targets for carbon intensity reduction in maritime the former and for sustainable aviation fuels penetration the latter.

Uncertainties in hydrogen market development persist despite new regulatory frameworks, specific funding program mechanisms (e.g., certificates of origins, contracts for difference) and strategic initiatives. Understanding the spatial demand for hydrogen is crucial for identifying suitable areas for new hydrogen projects and facilitating strategic investments by stakeholders in the market.

Regarding hydrogen estimation in industry, interesting studies are provided by (Neuwirth et al., 2022) and (Beck & Fischer, 2023). The former estimates hydrogen demand in Germany, starting from a process-specific and site-specific approach, based on the production output of 2018 for the energy-intensive industries. The study of Beck et al. adopts a holistic model, focusing on urban areas and employing various open-source data, including geodata and energy data. Hydrogen demand is obtained for industrial feedstock and process heating, but these analyses are limited at German cities and lack a comprehensive, georeferenced national-scale overview. In the assessment of hydrogen potential, the aforementioned articles calculate the demand for hydrogen by considering the entire thermal demand of industrial sites. They do not consider the possible role of other decarbonization strategies, such as electrification for low and medium temperature heat, that could mitigate the need for hydrogen.

Estimating hydrogen's role in aviation remains challenging, as the technology is still at very early stage of development, with research primarily focusing on fuel needs during flights rather than providing a georeferenced picture of consumption at airports. Fuel estimation from flight routes are proposed in (Wasiuk et al., 2015) or (Pagoni & Psaraki-Kalouptsidi, 2017), where data from air traffic are coupled with web-tools to evaluate greenhouse gas emissions and fuel consumption. However, these estimates refer to datasets that are not always publicly available or are related to commercial platforms. Furthermore, the focus of these studies is more related to the estimation of fuel consumption for specific aircraft classes rather than providing a georeferenced picture of fuel consumption at airports. An example of hydrogen estimation within the sector is provided in (Sacchi, 2023), where the energy vector needs from historical flight data of a specific Italian airport are assessed. However, a comprehensive regional or national-scale overview of the sector is lacking.

1.1 Aim of the paper and outline

This article addresses these gaps by undertaking a detailed spatial analysis of hydrogen demand in both industry and aviation, aiming to provide a comprehensive understanding of the geographical distribution of demand for renewable energy carriers. An Italian case study is presented, where the two

https://doi.org/10.52202/077185-0010

end-use sectors are analyzed. In the remainder of the paper, Section 2 describes the available data used, followed by the methodology for estimating hydrogen demand in industry (Section 3.1), aviation (Section 3.2) and with a focus on the refining sector (Section 3.3). An application of the developed method is then presented in Section 4, while key findings are summarized in the conclusion.

2 INPUT DATA

In this section the dataset used for the estimation of potential hydrogen demand in industry first and aviation sectors then are presented. All used information derives from open-access websites or online portals. In **Table 1** a summarized list of them is presented.

Table 1 *– Summary of main characteristics of the used datasets, divided by sectors; NUTS = European Union nomenclature of territorial units for statistics*

Dataset name	Sector of application	Spatial and/or temporal resolution	Brief description	Ref.
Industrial heat demand by temperature range and activity type	Industry	National for EU27 Member States, yearly data	Heat demand divided by temperature range and industrial subsector	(Kosmadakis, 2019)
Industrial electricity consumption	Industry	Provincial (NUTS 3) level, yearly data	Electrical load of Italian industrial subsectors	(Terna, 2019)
Industrial electricity and heat demand	Industry	National level and typical plant size, yearly data	Estimation of heat and electricity demand of industrial subsectors, identifying the overall national demand and that of a typical size plant	(GSE- Gestore dei Servizi Energetici, 2021)
N° of employees per activity type	Industry	Census section (subareas of a municipality)	Geographical distribution of manpower involved in different activity types within the country	ISTAT (Istituto Nazionale di Statistica, 2011)
N° of enterprises per activity type	Industry	Provincial (NUTS 3) level	Number of active industrial facilities involved in different subsectors within the country	ISTAT (Istituto Nazionale di Statistica, 2023)
Fossil resources trade in the market	Industry/ Aviation	Provincial (NUTS 3) level, monthly data	Volume, mass, energy exchanges of fossil resources traded in the market	(Ministero dell'ambiente e della sicurezza energetica (MASE), 2023)
N° of commercial flights from/to EU airports	Aviation	Punctual per airport, monthly data	Monthly commercial flights departing/arriving in the EU27 airports	(Eurostat, 2023)
Main destinations of flights from EU airports	Aviation	Punctual per airport, yearly data	Selection of top-5 main destinations of flights departing from EU27 airports	(Eurostat, 2021)

2.1 Data for industry

The industrial sector is characterized by a wide heterogeneity in processes and technologies needed, with consequent strong variation in energy needs and issues in their estimations.

A first dataset is contained in the 2019 paper by (Kosmadakis, 2019) where the author estimates the thermal energy demands in EU member states for the following industrial subsectors: (i) chemical, (ii) food and tobacco, (iii) iron and steel, (iv) machinery, (v) non-ferrous metals, (vi) non-metallic minerals, (vii) paper, (viii) textiles and leather, (ix) transport equipment, (x) wood industry and finally (xi) other. For these sectors, heat energy demand is identified and categorized by temperature ranges. Space heating and hot water production estimation are coupled with a detailed analysis of process heat, further divided into temperature ranges: (i) below 60°C, (ii) 60-80°C, (iii) 80-100°C, (iv) 100-150°C, (v) 150-200°C, (vi) 200-500°C, (vii) 500-1000°C, and (viii) above 1000°C.

The National Institute of Statistics (ISTAT) provides a complementary image of the Italian sector through a double set of data, thanks to which the industrial sites currently in operation are identified.

https://doi.org/10.52202/077185-0010

The first classification is represented by the Census of industry and services by ATECO code (Istituto Nazionale di Statistica, 2011), corresponding to the NACE classification (European Union, 2023), which establishes a classification of economic activities to be used across the European Union. In the ISTAT database the number of employees of each economic activity is given with a census section spatial resolution, using the NACE classification with a three-digit granularity detail. The reported information refers to the year 2011, the last year in which a complete census was carried out on the entire country and therefore representative of the sector.

ISTAT published a second dataset, where active enterprises are listed and classified by NACE code (but only at two-digit level) with a provincial spatial resolution (Istituto Nazionale di Statistica, 2023). These are categorized based on the size of their workforce employed as follows: (i) activities with between 1 and 9 employees, (ii) 10-49, (iii) 50-249, and finally (iv) above 250. The lower number of NACE digits can determine some classification issues for industrial subsectors, by grouping together very heterogeneous industrial processes with different specific heat requirements.

Another set of information is provided by GSE, the Italian authority for the promotion and the development of renewable energy sources and energy efficiency. In (GSE- Gestore dei Servizi Energetici, 2021), an overview of the heating and electricity needs for various industrial sectoral aggregations, relating to the year 2018, is identified. The study provides information about small and medium-sized enterprises (with between 10 and 50 employees) and medium-sized enterprises (with more than 50 employees), by distinguishing specific manufacturing activities. For the former GSE estimates energy needs for: (i) chemical, which includes pharmaceuticals and plastics, (ii) coke industry, (iii) refining, (iv) food, (v) steel, (vi) mechanical industry, (vii) non-ferrous metals, (viii) ceramics and glass and (ix) paper. Related to medium-sized enterprises, information is provided also for: (x) textiles, (xi) automotive and (xii) wood processing. Spatial resolution is limited at national level, but GSE also provides the energy needs for typical size plants.

A further set of information is made available by Terna, the Italian system operator of the electricity transmission grid, through the online portal "Statistical Publications" (Terna, 2019), where data about electricity consumption can be downloaded for different years. The spatial resolution is at provincial level, with the information that covers various end-use sectors. Focusing on industrial activities, the granularity of the data follows a logic in line with the NACE classification (comparable with a two-digit level of detail), facilitating the combination with ISTAT datasets.

An alternative classification of the end-use sectors is possible by analysing the respective fuel consumption. In (Ministero dell'ambiente e della sicurezza energetica (MASE), 2023) the monthly fossil resources trade in the market, with different spatial resolutions and differentiating by final use, are published. A dataset with national aggregations of different fossil fuels, is provided. The included categories are: (i) network, (ii) end consumers, (iii) agriculture, the transport sector with respectively (iv) railways, (v) small navy and (vi) aviation, (vii) power utilities, (viii) military forces, (ix) retailers, (x) industry and (xi) other. By way of example, fuels on the list include conventional road transport fuels, aviation fuel, bitumen, motor diesel, various lubricants, liquid petroleum gas and other biofuels.

2.2 Data for aviation

Regarding the aviation sector, energy demand can be assessed through an indirect approach, by focusing on air mobility demand and spatially allocating specific fuel consumption.

The first list of data available is published by Eurostat, the statistical office of European Union, on its online platform (Eurostat, 2023), assessing the history of flights from domestic airports to different locations in Italy and abroad, from 2010 onwards. Among other information, the monthly number of departures and arrivals for each EU airport by commercial routes are made available.

There are several classifications to identify airports, although the most internationally recognised is the IATA classification provided in (International Air Transport Association (IATA), 2023). In this dataset a unique three-digit nomenclature is assigned to each airport. However, in the list some lacks of information are observed, particularly in relation to smaller-scale airports.

A supplementary set of data is then provided by the online open-source platform (Datahub, 2024). Here a list of airports is presented, divided by type (e.g., airports or heliports) with additional information that combine the name of the airport with both geographical coordinates (i.e., latitude and longitude) and administrative information (e.g. municipality, country).

https://doi.org/10.52202/077185-0010

In the process of estimating specific fuel consumption per flight, valuable information can be obtained from (International Civil Aviation Organization (ICAO), 2023). ICAO provides an online tool that allows the assessment of greenhouse gas emissions and the associated aviation fuel consumption for a specific flight, once the departure and arrival airports are defined. The latter is not a true dataset but can be constructed through a series of queries to the tool using selected air trade routes. The process of identifying the most relevant air routes can take advantage of another list of information, provided by the European Commission (Eurostat, 2021). The EU authority provides an online platform showcasing the top five routes for the main airports (by number of movements) in each Member State. This information includes metrics for both passengers involved and flights operated.
The previous data are finally compared and integrated with dataset of fossil fuel national consumption in aviation provided by Ministry of Environment and Energy Security (Ministero dell'ambiente e della sicurezza energetica (MASE), 2023), also used for the analysis on the refining sector.

3 METHODOLOGY

In this Section the methodology to estimate the potential hydrogen demand and its distribution across the Italian energy system is presented. The first chapter details the industrial sector and its sub-categories, followed by a description regarding the aviation and its interlinkages with the refining sector, presented in the bottom part of the Section. In **Figure 1** a graphical flowchart describes the used dataset and the methodological steps implemented.

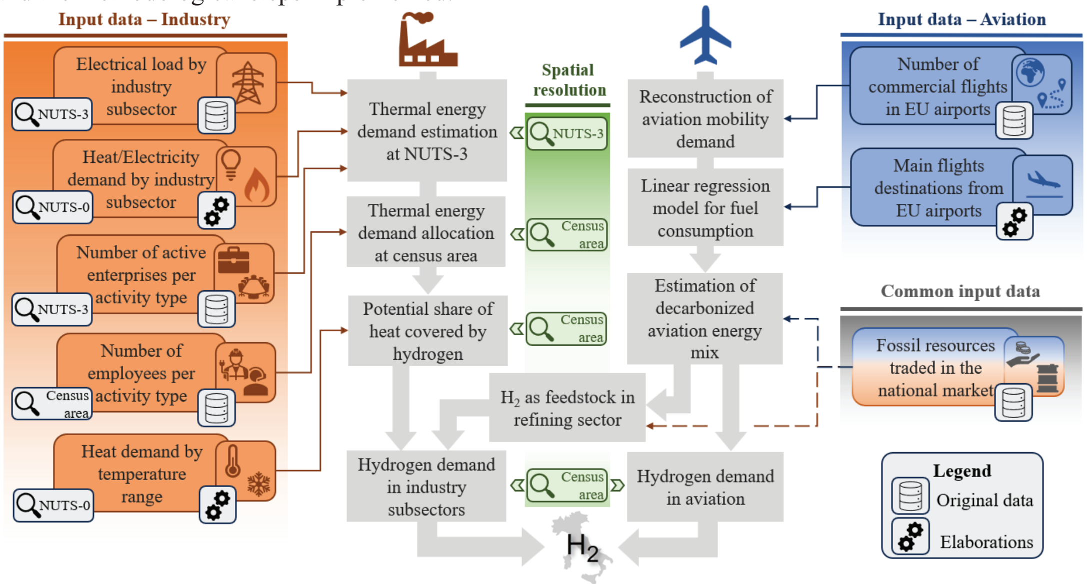

Figure 1 – Schematic flowchart of the developed methodology and used dataset within the study

3.1 Industrial sector

In the context of the industry, the presented approach aims first to estimate and spatially characterize the energy needs of each sub-categories. Then, with the obtained thermal energy demand, an evaluation of the share that could potentially be supplied by hydrogen technology is provided, and finally, the overall hydrogen demand is computed.
The starting point is the historical electricity consumption data for various manufacturing classes provided by the Italian transmission system operator Terna, with provincial spatial resolution for 2019[2] (Terna, 2019). These data serve as the basis for developing a spatial characterization of the sector, to further estimate the related thermal energy needs. In this endeavour, GSE published estimates in the 2022 report (GSE- Gestore dei Servizi Energetici, 2021) for both electrical and thermal energy demands

---

[2] The year has been selected for being representative of the situation before the pandemic and the strong instability in the international context.

https://doi.org/10.52202/077185-0010

in specific manufacturing activities. These estimates are available at national level and include values for typical-sized users. An average ratio between thermal and electrical needs of a typical plant can be then derived, differentiating it for the reported categories of manufacturing activities.

The main challenge with this method arises from the heterogeneous classifications of industrial activities across different data sources. In the present study, the authors reorganized and grouped the different datasets to closely align with the NACE definition. As an illustration, GSE distinguishes between "steel activities" and "non-ferrous metal production", while Terna identifies only the class "metallurgy", adhering to the two-digit NACE definition.

For the estimation of the industrial thermal energy demand, the merging of datasets is weighted. GSE dataset includes estimates of the power and heat demand for small-to-medium scale enterprises and for medium-to-large scale ones. The former is characterized by up to 50 workers, while the latter corresponds to firms with 50 or more workers. Since this dataset provides estimations at national level and also for a typical-sized user for each subsector, the ratio between the national values and the ones for small and large plants returns an initial approximation of the number of enterprises in that industrial subsector. ISTAT then provides the number of currently active companies per province, categorizing them by classes of employees (with a two-digit NACE code) (Istituto Nazionale di Statistica, 2023), and identifying the number of employees by NACE classification (with a three-digit code) with municipal detail (Istituto Nazionale di Statistica, 2011). This approach enables the estimation of the number of small, medium and large enterprises at each NUTS 3 level and subsequently establishes a weighted ratio between power and thermal energy demand for each manufacturing section from values identified by GSE. As an example, starting from the electricity consumption in the "metallurgy" class of a specific province, the related thermal need is obtained by considering the presence within the territory of active enterprises and employees of "steel activities" and "non-ferrous metal production".

The subsectors for which thermal needs are estimated at the provincial level include the following: (i) metallurgy, (ii) food, (iii) textile, (iv) wood processing, (v) paper, (vi) refining, (vii) non-metallic minerals (e.g., concrete, ceramics, and glass), (viii) chemicals and (ix) automotive production and other means of transport. However, due to the lack or incompleteness of information from different sources, not all the original NACE manufacturing activities are sufficiently detailed in the final list.

To achieve greater spatial granularity, the snapshot of the number of industrial employees provided by ISTAT is used again. For instance, the provincial thermal demand in "metallurgy" class is distributed at the census section, through a weighting of the number of employees in the respective manufacturing sector within the boundaries of the considered province. It should be noted that the ISTAT data do not refer to the same year as that evaluated in the analysis (i.e., 2011 v. 2019). This can lead to uncertainties arising from their use, namely the risk to consider enterprises that might have ceased (or moved) their activities after 2011 as potential points for energy demand. However, due to the limited availability of information in the literature, these possible uncertainties are considered as acceptable.

The following step is to evaluate the type of heat required, to assess the technology needed for its generation and estimate the potential share that could be covered by hydrogen. A possible categorisation involves the use of the operating temperature ranges, as presented in (Kosmadakis, 2019). The study provides estimates for thermal demand for hot water production and space heating and a classification of process heat used in various industrial subsectors. Currently, thermal energy for industrial processes is primarily supplied by combustion systems, with few electrified exceptions (e.g., arc furnaces in metallurgy). Renewable technological options, such as industrial electric heat pumps, are entering in the market for temperature ranges currently around 100-120°C, with some prototypal units reaching 160°C. Further development and an increase in the supply of high temperatures can be expected in the coming years, with current research projects focusing in the range of 160-200°C (Marina et al., 2021). For process heat at higher temperatures (e.g., above 200°C) electrified solutions are already currently possible, although they still face some limitations. For instance, they are constrained by heat capacity limitations, often encountering issues related to plant complexity, volume requirements, or transient time required to reach specific operating conditions.

Kosmadakis analyses different EU Member States, including Italy, and identifies several manufacturing classes. For each of them, he defines different categories of required heat. In this article, the classification is reorganized and grouped as follows: (i) heat to be supplied for space heating, (ii) for the production of domestic hot water, (iii) process heat up to 200°C, and (iv) heat at higher temperatures.

https://doi.org/10.52202/077185-0010

The classification of industrial subsectors adopted by Kosmadakis differs slightly from the one presented in the article. The author does not analyse the refining sector, which is included in the article. Most refining processes take place in the temperature range between 200 and 1000°C. In the present article, the heat distribution assigned to refining sector is assumed to be the same one Kosmadakis identifies for chemical sector, where about 65% of the estimated required heat is included in this temperature range. A second issue concerns the class of automotive production and other means of transport. Unlike other EU Member States analysed, no information is provided for the Italian case by Kosmadakis. Average values for Euro-zone are then applied for the national case study.

The last step concerns the definition of the primary energy mix required to provide such amounts of heat. While high-efficiency electrified solutions are already commercially available in the market for space heating and hot water production, electric solutions, like industrial heat pumps, face some technical constraints for the share of process heat below 200°C. The need for electric heat pumps to use a heat source at a lower temperature (but with not an excessive temperature difference) led to the assumption that only a part of this process heat could be supplied through electrification. The remaining process heat demand is assumed to be provided only through combustion processes. Finally, assuming an average efficiency for the combustion process equal to 80% (based on lower heating value) and considering a combustor designed for pure hydrogen injection, an estimation of H_2 demand is obtained. Regarding the sub-sector of refining, additional comments are presented after the definition of the aviation energy needs in the following section.

3.2 Aviation sector

In this section the methodology for determining the potential hydrogen demand in aviation is presented. This estimation highlights the need to also focus on the refining sector, which is described in the following section. The steps for estimating air mobility demand are introduced, followed by considerations on the aviation fuel consumption mix to finally estimate the hydrogen demand.

Concerning mobility demand, Eurostat publishes historical data (from 2010 onwards) of the number of flights operated by airports on the continent, also specifying the number of passengers transported. The Italian Civil Aviation Authority identifies 45 airports currently in operation for commercial flights within the national boundaries. However, Eurostat provides information only for 38 of them, excluding smaller airports. The absence of flights information for these smaller airports is considered acceptable, given that the discrepancy between the number of flights and the travelling passengers between the two source of data is less than 1.5% and 0.5%, respectively. Furthermore, it is reasonable to assume that these excluded airports are not the departure points for the longest air routes, which significantly contribute to the overall aviation fuel consumption. Eurostat data help identify the air traffic routes for each airport, enabling the reconstruction of distances travelled between the departure and destination airports. Subsequently, these distances are associated with fuel consumption values empirically derived as presented below.

To mitigate potential misunderstanding arising from the locations of departures and arrivals (e.g., municipalities associated with more than one airport, such as Milan, with Linate and Malpensa), a standardized terminology is essential. This standardization is achieved by combining datasets from the online platform (Datahub, 2024) and supplementing the information with codes from (International Air Transport Association (IATA), 2023), which are not always available, especially for airports with lower air traffic.

Geographical coordinates are assigned and air distances between take-off and landing airports for each considered flight are then estimated. For this analysis, only commercial flights are selected, excluding those dedicated to cargo transport. This choice is primarily due to the wide heterogeneity of aircrafts categories used in the cargo transport and the scarcity of information available in the literature.

In parallel, a linear regression model is developed to estimate the consumption associated with each flight departing from national airports, establishing a correlation between the amount of fuel consumed (in terms of mass) and the distance travelled (in kilometres). Utilizing the online portal Carbon Emissions Calculator (International Civil Aviation Organization (ICAO), 2023), an estimation of the required fuel, for a selected number of specific routes, is obtained and associated with the related air distance in the regression model. The selection of these routes is calibrated to characterize the most travelled routes and to evaluate different types of flights. Depending on the distance to be covered,

https://doi.org/10.52202/077185-0010

different aircraft classes are assigned. For instance, on intercontinental routes, significantly larger (and heavier) aircraft models are preferred to maximize the number of passengers transported and the space allocated for fuel, thereby achieving greater flight autonomy. It is reasonable to expect that fuel consumption and related emissions vary compared to alternatives for aircraft used on shorter routes. A threshold between different consumption behaviours is observed around 3000 km and, for these reasons, two classes are identified: (i) short and medium-haul flights, covering distances less than 3000 km, and (ii) long-haul flights, including other types of intercontinental flights. A linear correlation between air distance and expected fuel needs is derived for each class. Given that the primary aircraft propulsion system (excluding smaller planes, not considered in the analysis) consists of gas turbines fuelled by kerosene, defining the fuel's energy properties allows for estimating the energy consumption in terms of primary energy required to supply each individual airport.

Regarding the supply-chain, the conventional method for synthesizing aviation fuel (i.e., kerosene) is through the Fischer-Tropsch process. A gaseous mixture composed of carbon and hydrogen molecules, usually in the most common forms of carbon monoxide (CO) and hydrogen (H_2), is fed into a series of chemical reactors to produce various fuel classes, including kerosene. This production line could be decarbonized by replacing the source of the elements used as feedstock. Instead of utilizing synthesis gas obtained from the gasification and/or recombination of other fossil fuels, a potential solution could involve the use of green hydrogen (produced, for example, through electrolysis and renewable electricity) and carbon dioxide removed from the atmosphere or from biogenic sources.

In a prospective view of the future energy mix, even considering a long time horizon (i.e., 2050), there is consensus in the literature that a full electrification of the aviation sector is highly improbable. Therefore, it is reasonable to expect that the primary share of energy needs will realistically be met through the use of synthetic fuels. These fuels, while similar in thermodynamic properties to conventional fossil fuels, are characterized by zero climate-altering impact. Alternative solutions, such as hydrogen and electric propulsion, are expected to play a minor role.

The potential hydrogen demand for aviation is then composed of a fraction used in its pure form as fuel, which can be allocated directly to airports, and the amount needed for the production of synthetic kerosene, which must be assigned to refining plants. The latter information is derived from the estimated mass and energy balances provided by the 2022 report (Concawe & Aramco, 2022) by the division of the European fuel manufacturers association dealing with environmental sciences for European refining. Therefore, a further in-depth analysis of the refining sector is necessary.

3.3 Refining sector

When considering the decarbonization of the refining sector, the potential green hydrogen demand is influenced by various interconnected factors. This includes not only the needs of H_2 for industrial heating in thermochemical processes, but also its use as secondary feedstock. Today hydrogen is used in tasks such as removing impurities from fossil sources (e.g., desulphurization) or producing specific complex compounds. As the main outputs of the refineries are transport fuels, decarbonizing mobility is expected to significantly change (and likely reduce) the need for treating fossil feedstocks in refining plants. To decarbonize the remaining quantities of fuels and chemicals, substituting fossil-based raw materials with hydrogen and carbon-based molecules from sustainable supply-chains is considered.

Estimations are derived from monthly data on mass and energy exchanges of fossil resources traded in the Italian market and produced in refineries, provided by the Italian Ministry of the Environment and Energy Security. By defining the average chemical characteristics of each refining product, a preliminary estimation of the required hydrogen and CO/CO_2 to replace these fossil compounds can be provided.

The main challenge lies in the strong heterogeneity of the considered energy vectors. Chemical reactors produce mixtures of various compounds with varying composition, depending on the fuel/product (whose yield is to be maximized) and the origin of the fossil feedstock. For instance, for crude oil, depending on the origin (e.g., the Middle East or the United States), hydrocarbons (and therefore the number of carbon and hydrogen atoms that constitute them) vary significantly. A simplified approach is adopted, defining the specific molecular composition of each refining product by identifying the most common chemical compound for each class. For instance, the category of light fractions, encompassing molecules with a carbon chain length typically ranging approximately from C_4 to C_{10}, is assumed to be

https://doi.org/10.52202/077185-0010

represented by octane, with the chemical formula $C_8 H_{18}$. This helps in determining the molar ratios of hydrogen and carbon dioxide required for production, identifying the molecules of finished products and their thermodynamic properties like calorific value and molar mass.

Despite the complexity and heterogeneity of the treated products, this methodology provides a useful first attempt to estimate the magnitudes of hydrogen required for decarbonizing the refining industry.

4 CASE APPLICATION

The presented method allows for the estimation of hydrogen demand within the two sectors across a wide range of possible scenarios, taking into account different boundary conditions (e.g., time horizon, deployment of H_2-based technology). In this section, a case application in line with 2050 net-zero decarbonization target is presented, outlining the main assumptions and the resulting outcomes.

As a long-term snapshot analysis, it is assumed that renewable technologies have reached complete maturity and are widely distributed in the market, implying the hydrogen production entirely achieved through renewable energy sources. Concerning the industry, it is assumed that all existing facilities remain operational in the tested case study, with the same thermal energy needs estimated from historical data. The heat demand (including space heating, hot water and process heat) is supplied by electrified solutions for lower temperatures, assuming the availability of electrical heat pumps up to 200°C and hydrogen combustion for higher temperatures. Electrified solutions for space heating and hot water production are commercially available, eliminating the need for combustion systems. For the portion of process heat up to 200°C that could be supplied through industrial electric heat pumps, the same estimates as those used by Kosmadakis are applied. Regarding process heat at higher temperatures, hydrogen combustion is considered as the sole technology option to assess the maximum role of low-carbon hydrogen in the sector.

In the aviation sector, the 2050 air mobility demand is assumed to increase by 44%, aligning with the base scenario estimated by Eurocontrol in its 2050 aviation outlook (Eurocontrol, 2022). The list of existing national airports is confirmed in the tested scenario, maintaining the same flight routes, which are increased proportionally with the average expected growth. The aviation energy mix is then assumed to be composed of 70% sustainable aviation fuels, with half of that total derived from renewable fuels of non-biological origins. Within this, 10% is assumed from pure hydrogen and the remaining share (i.e., 25%) is from e-kerosene, as outlined in the 2023 RefuelEU aviation package proposal (European Council & Council of the European Union, 2023b).

Finally, concerning the refining sector, the fuels intended for transport purposes are reduced as follows: since the current national production of aviation fuels (i.e., carboturbo jetfuel) is at the same order of magnitude as the estimated e-kerosene energy needs for the tested case study, it is assumed that the latter is entirely supplied by national refineries. For other modes of transportation, global trends proposed by IEA in the Net-Zero by 2050 report (IEA, 2021) are used to assess the reduction in fossil fuels and the consequent demand for synthetic ones. The expected refining production is then determined by keeping the amount of chemical compounds destined for other industrial uses constant, excluding heavy oils for industrial power generation, which are expected to be phased out.

Given the aforementioned assumptions, **Figure 2** and **Table 2** present the expected results in the two sectors. On the left, **Figure 2** displays the geographical distribution of the annual hydrogen demand in industry, while on the right, it provides a regional aggregation of the energy carrier needs in the aviation and refining sector (as shown in **Table 2**, with the addition of the industrial energy needs). The representation is at the NUTS-2 level due to the limited number of sites where the hydrogen demand would be located.

Industrial energy needs are significantly influenced by the refining, as the decarbonization of outputs from the 15 national facilities would result in a hydrogen demand of approximately 433 TWh/y (out of a total of ~596 TWh/y for the overall demand, equal to 18 Mt_{H2}/y). The annual utilization of pure hydrogen in aviation is expected to reach almost 9 TWh, with just four airports absorbing around 75% of the national demand (in Rome, Milan and Bergamo provinces) and 76% in just two regions.

https://doi.org/10.52202/077185-0010

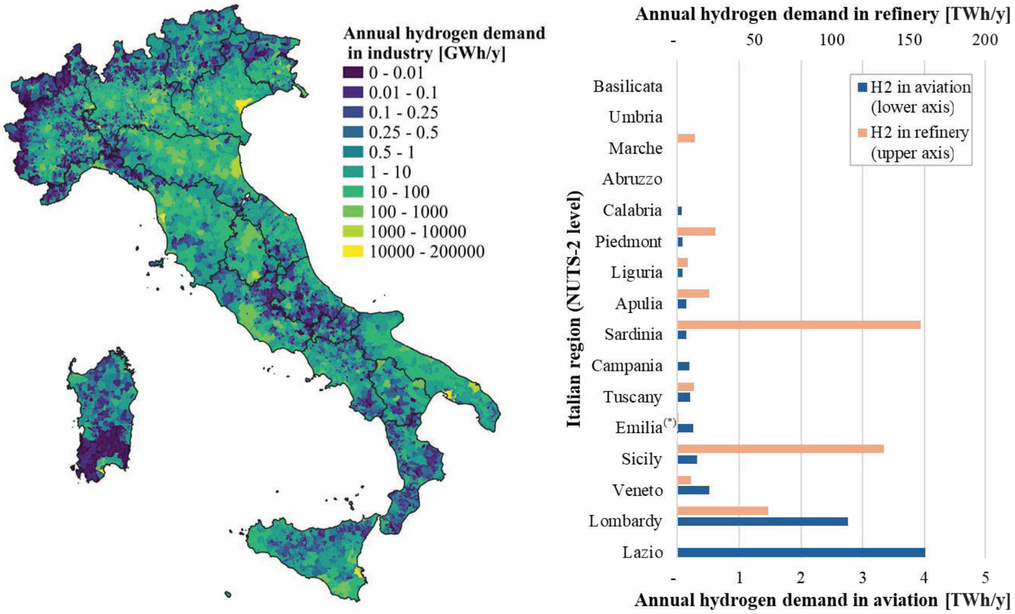

***Figure 2** – (on the left) Spatial distribution of estimated annual hydrogen demand in industry, including refining plants; (on the right) annual hydrogen demand in aviation and refining sector at NUTS-2 level; Note that only Italian regions with non-zero values are shown, for sake of representation; (*) Emilia-Romagna*

***Table 2** – Estimated annual hydrogen demand at NUTS-2 level categorized by sector type*

H_2 demand [TWh/y]	Aviation	Refining sector (as feedstock)	Industry (for thermal needs)	H_2 demand [TWh/y]	Aviation	Refining sector (as feedstock)	Industry (for thermal needs)
Lazio	4.0	-	3.5	Piedmont	0.08	24.4	8.7
Lombardy	2.8	58.9	39.7	Calabria	0.07	-	0.5
Veneto	0.52	8.7	14.6	Abruzzo	0.01	-	1.6
Sicily	0.32	133.7	15.1	Marche	0.01	11.2	2.1
Emilia-Romagna	0.26	0.6	13.7	Umbria	0.004	-	4.8
Tuscany	0.21	10.6	8.3	Aosta Valley	-	-	0.8
Campania	0.19	-	2.6	Trentino-Alto Adige	-	-	2.3
Sardegna	0.14	157.6	15.2	Friuli-Venezia Giulia	-	-	7.9
Apulia	0.14	20.5	8.7	Molise	-	-	0.7
Liguria	0.08	6.5	1.8	Basilicata	-	0.3	1.2
				Italy	**9**	**433**	**154**

Finally, **Table 3** lists the aggregated national results by end-use. This initial assessment highlights the strong interconnections between end-use sectors in the decarbonization process. Achieving net-zero transport targets would directly impact the refining sector, with a hydrogen demand that could constitute one-third of the estimated total for the e-fuels synthesis, while an additional 30% might be required for the production of other chemical compounds, 26% for industrial thermal needs and only 1.4% as a pure energy carrier in aviation.

https://doi.org/10.52202/077185-0010

Table 3 *– Estimated hydrogen annual demand categorized by use and sector type; (on the left) for industrial thermal needs, (on the right) for decarbonizing refining products, for direct use in aviation and the overall total*

Expected H_2 demand in industry for thermal needs [TWh/y]		**Expected H_2 demand in refining sector as feedstock [TWh/y]**		
Refining	37.9	E-fuels synthesis	For road	115.6
Chemical	18.6		For aviation	28.2
Food & beverage	11.1		For shipping	49.5
Iron and steel	22.2		For rail	2.2
Non-ferrous materials	22.9	For other industrial chemical compounds		237.6
Non-metallic minerals	28.9	**Total in refining (as feedstock)**		**433**
Pulp and paper	8.8			
Textile	2.4	**Expected H_2 demand in aviation [TWh/y]**		
Wood processing	0.6	For direct use in aircrafts		8.8
Transport equipment	0.2			
Total in industry (for thermal needs)	**153.7**	**Total**		**595.5**

5 CONCLUSION

This study introduces an innovative methodology for estimating potential hydrogen demand in the industrial and aviation sectors with a high spatial resolution. The adopted framework evaluates thermal energy needs in various industrial sectors that may not be easily electrified. Hydrogen demand is also calculated for refining processes and aviation decarbonization. For the former, an approach based on associating chemical compounds to each refining product is presented. For the latter, a fuel consumption regression model based on air mobility demands is developed. This scheme, based on open-source datasets, is designed for Italy but is replicable for other regions or adaptable depending on data availability. It provides valuable information for defining and analyzing decarbonization scenarios and pathways. As demonstrated by the presented case study, the potential application of the method in further investigating the role of the green molecule in decarbonizing energy systems is evident. Results underscore the crucial role of decarbonizing the transport energy mix, with refineries playing a key role in the magnitude of potential hydrogen demand. In this case study, e-fuel synthesis alone might represent one-third of the overall estimated hydrogen needs (i.e., 195 out of ~600 TWh/y), with another 30% destined for supplying industrial chemical compounds and 26% for industrial thermal needs. Further improvements could focus on enhancing the estimation of hydrocarbon composition in refineries and allocating thermal needs per temperature range within the industrial subsectors.

NOMENCLATURE

EU	European Union
NACE	Nomenclature of Economic Activities
NUTS	European Union nomenclature of territorial units for statistics

BIBLIOGRAPHY

Beck, S., & Fischer, D. (2023). A methodological framework for geospatial modelling of hydrogen demand in cities. *Energy Informatics*. https://doi.org/https://doi.org/10.1186/s42162-023-00291-2

Concawe, & Aramco. (2022). *E-Fuels: A techno-economic assessment of European domestic production and imports towards 2050*.

Datahub. (2024). *Airport Codes*. https://datahub.io/core/airport-codes

Eurocontrol. (2022). *Eurocontrol - Aviation Outlook 2050*.

European Commission. (2023). *Net-Zero Industry Act*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en

European Council, & Council of the European Union. (2021). *Fit for 55*.

https://doi.org/10.52202/077185-0010

https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

European Council, & Council of the European Union. (2022). *REPowerEU: energy policy in EU countries' recovery and resilience plans*. https://www.consilium.europa.eu/it/policies/eu-recovery-plan/repowereu/

European Council, & Council of the European Union. (2023a). *FuelEU maritime initiative*. https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/

European Council, & Council of the European Union. (2023b). *RefuelEU aviation initiative*. https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/

European Union. (2023). *Statistical classification of economic activities – NACE Revision 2.1*. https://eur-lex.europa.eu/EN/legal-content/summary/statistical-classification-of-economic-activities-nace-revision-2-1.html

Eurostat. (2021). *Air passenger transport 2021*. https://ec.europa.eu/eurostat/cache/infographs/airports/

Eurostat. (2023). *Air transport of passengers by airport and type of transport*. https://ec.europa.eu/eurostat/web/main/data/database?p_p_id=NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_nPqeVbPXRmWQ&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view

GSE- Gestore dei Servizi Energetici. (2021). *Valutazione del potenziale nazionale e regionale del riscaldamento efficiente*.

IEA. (2021). *Net Zero by 2050, A Roadmap for the Global Energy Sector*.

International Air Transport Association (IATA). (2023). *International Air Transport Association - Official website*. https://www.iata.org/

International Civil Aviation Organization (ICAO). (2023). *Carbon emissions calculator*. https://applications.icao.int/icec/Home/Index

Istituto Nazionale di Statistica. (2011). *9° Censimento industria e servizi 2011*. https://www.istat.it/it/censimenti-permanenti/censimenti-precedenti/industria-e-servizi/imprese-2011

Istituto Nazionale di Statistica. (2023). *Imprese e addetti: Classe di addetti, settori economici (Ateco 2 cifre) - prov.* http://dati.istat.it/Index.aspx?QueryId=20596#

Kosmadakis, G. (2019). Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. *Applied Thermal Engineering*, *156*, 287–298. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2019.04.082

Marina, A., Spolestra, S., Zondag, H. A., & Wemmers, A. K. (2021). An estimation of the European industrial heat pump market potential. *Renewable and Sustainable Energy Reviews*, *139*. https://doi.org/https://doi.org/10.1016/j.rser.2020.110545

Ministero dell'ambiente e della sicurezza energetica (MASE). (2023). *Bollettino petrolifero*. https://dgsaie.mise.gov.it/bollettino-petrolifero

Neuwirth, M., Fleiter, T., Manz, P., & Hofmann, R. (2022). The future potential hydrogen demand in energy-intensive industries - a site-specific approach applied to Germany. *Energy Conversion and Management*, *252*. https://doi.org/https://doi.org/10.1016/j.enconman.2021.115052

Pagoni, I., & Psaraki-Kalouptsidi, V. (2017). Calculation of aircraft fuel consumption and CO2 emissions based on path profile estimation by clustering and registration. *Transportation Research Part D: Transport and Environment*, *54*, 172–190. https://doi.org/http://dx.doi.org/10.1016/j.trd.2017.05.006

Sacchi, G. (2023). *Electrification and hydrogen use in aviation: a scenario-based simulation of Turin airport*. Politecnico di Torino.

Terna. (2019). *Statistiche regionali 2019*.

Wasiuk, D. K., Lowenberg, M. H., & Shallcross, D. E. (2015). An aircraft performance model implementation for the estimation of global and regional commercial aviation fuel burn and emissions. *Transportation Research Part D: Transport and Environment*, *35*, 142–159. https://doi.org/http://dx.doi.org/10.1016/j.trd.2014.11.022

https://doi.org/10.52202/077185-0010